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8. The desirable average length of a paper is about 12,000 words and the absolute maximum is 18,000 words. As an approximation, each full page of typed text, table, or illustration is the equivalent of 300 words.

9. Technical papers intended for publication must be written in the third person.

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AIRPLANE PERFORMANCE AND THE SMALL AIRPORT

By Walter E. Gillfillan,[1] M. ASCE

SYNOPSIS

The effect of airplane performance on small airport runway length and runway approaches is illustrated herein. This analysis also indicates the importance of the availability of performance data, not only for the pilot, but for the airport designer.

INTRODUCTION

Civil engineers undertaking the design of small airports are frequently unaware of the effect of the performance of general aviation airplanes on the airport. The importance of considering the characteristics of the airplane are demonstrated by indicating the range of performance that can be expected, showing how this varies with environment, and translating the performance characteristics into runway and approach requirements.

The character, use, and type of aircraft that are used in general aviation flying are summarized in Table 1. This table divides use into four categories: Business, commercial, pleasure, and instructional. Among these categories, pleasure flying accounts for far more planes than the other—45%—nearly all of them single-engine. But business flying accounts for far more hours flown than the others—45%. Although most business flying is done in single-engine airplanes such flights utilizes the largest number of multiple-engine air-

Note.—Discussion open until August 1, 1961. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Air Transport Division, Proceedings of the American Society of Civil Engineers, Vol. 87, No. AT 1, March, 1961.

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planes. All in all, 80% of the general aviation airplanes are single-engine, with less than 2% exceeding a maximum gross weight of 12,500 lb.

Table 2 shows the numbers and percentages of prevalent models, grouped by engine class and manufacturer. Of the models listed, over 50% were manufactured prior to 1950. This is of importance because these older planes (as well as certain new ones) require significantly more runway length and approach clearance under certain altitude and temperature conditions.

Before beginning a detailed discussion of performance, it may be helpful to review those parts of the Civil Air Regulations that affect the manufacturer's certification of airplane performance during take-off, landing, and initial climb.

CIVIL AIR REGULATIONS

General aviation airplanes are certified under Part 3 of the Civil Air Regulations in three categories, normal, utility, and acrobatic. A normal

TABLE 1.—COMPOSITION OF GENERAL AVIATION ACTIVITY, 1957[a]

Primary Use	Number of Single Engine Airplanes				Number of Multi-Engine Airplanes		Total Airplanes By Primary Use		Total Hours Flown	
	One and Two Place		Three or More Places							
	Less than 100 hp	Greater than 100 hp	Less than 145 hp	Greater than 145 hp	Total 800 hp or less	Total greater than 800 hp	Nos.	Percent of Total	Hrs. mil.	Percent of Total
Business	2390	860	1520	12450	2610	1630	21460	32.6	4.8	45.0
Commercial	2010	4110	190	1950	480	450	9190	13.9	2.1	19.0
Pleasure	17280	1600	3530	7110	140	c	29660	45.0	2.1	19.0
Instructional	3830	290	340	1130	60	-	5650	8.5	1.9	17.0
Total[b]	25510	6860	5580	22640	3290	2080	65960	100.0	10.9	100.0

[a] U. S. Federal Aviation Agency, General Aviation Aircraft Use, September, 1959.
[b] Excludes gliders and helicopters.
[c] Less than 5 aircraft.

catagory airplane is defined as one in non-acrobatic or nonscheduled passenger or cargo use. This is the category under which most general aviation aircraft are certified. A utility category airplane is one having the same uses as the normal but for which certain acrobatic maneuvers are permitted. Many general aviation airplanes have both the normal and utility certification to allow the airplane to be used in all phases of flight instruction. The maximum allowable gross weight, however, is usually less in the utility than in the normal category. In the acrobatic category there are no restrictions to serial maneuvers. This category has limited application.

The take-off requirements for general aviation airplanes are described in Part 3 of the Civil Air Regulations by the definition of take-off distance. This distance is defined as the distance from start of take-off roll to attaining

a 50 ft height above the ground. The duplication of this performance cannot require any exceptional piloting skill or unusually favorable conditions.

For multi-engine general aviation airplanes there is no Civil Air Regulations requirement for continuance of take-off with an engine failure as with transport category airplanes.

The landing distance for general aviation airplanes is defined by the Civil Air Regulations as the distance from 50 ft over the threshold to a complete stop. Again, no exceptional skill or conditions must be required to duplicate the maneuver.

For climbing conditions, the Civil Air Regulations require a minimum rate of climb of 300 fpm at sea level and a steady climb angle of at least 1:12 (8.33%) for airplanes greater than 6,000 lb gross weight. For single engine airplanes less than 6,000 lb the climb rate must be ten times the true indicated stall speed or 300 fpm, whichever is greater. Multi-engine airplanes with stall speeds above 70 mph must have a climb rate equal to 0.02 times the stalling speed (in miles per hour) squared. This must be demonstrated at 5,000 ft altitude with one enginer inoperative.

In the past, the manufacturers were required to provide the take-off and landing data in the airplane flight manual together with the effects of pressure altitude and temperature upon this performance. Presently, the Civil Air Regulations requires this information in the flight manual only if the gross weight of the airplane exceeds 6,000 lb. (Several of the manufacturers voluntarily include in the airplane flight manual for all of their airplanes the effects of pressure altitude and temperature upon the take-off, landing, and climb characteristics.)

AIRPLANE PERFORMANCE

Runway Length.— The regulations affecting the runway requirements for general aviation airplanes are not nearly as detailed or restrictive as those for the transport category. Because of the variations in size, horsepower, and features, however, the performance of many of these smaller airplanes has a profound effect on airport design. The range of this effect is illustrated in Figs 1 and 2. The data used in this analysis are from the manufacturers', Civil Aeronautics Administration (CAA), or Federal Aviation Agency (FAA) approved flight manuals. In order to show the airplane performance and the relation of environmental effects, certain conditions were assumed. These conditions were as follows:

1. Pressure altitude - sea level standard atmospheric pressure 29.92 in. of mercury.
2. Temperature - sea level standard 59°F.
3. Wind - zero
4. Runway - level, hard-surfaced.
5. Flaps - zero (unless otherwise noted by manufacturer for normal take-off).
6. Maximum allowable gross weight.
7. Climb slope - computed from maximum rate of climb and best climb true air speed (if applicable, gear and flaps retracted).

TABLE 2.—PREVALENT ACTIVE GENERAL AVIATION AIRPLANES[a,b]

Manufacturer and Model (1)	Total Active Airplanes (2)	Percentage of Total Active Multi- and Single Engine Airplanes (3)
MULTI-ENGINE:		
Aero Design and Engr. Co.		
(Aero Commander) 520	108	0.16
(Aero Commander) 560, 560A, 560E	163	0.25
(Aero Commander) 680, 680E	202	0.31
(Aero Commander) 720	3	-
Beech Aircraft Corp.		
AT 11[c]	109	0.17
C18S, D18S, E18S	927	1.41
B45[c]	158	0.24
50, B50, C50, D50, E50, F50, G50	453	0.69
95 (Travel Air)	168	0.26
Cessna Aircraft Company		
T50[c]	196	0.30
310, 310A, 310B, 310C	629	0.96
deHavilland Aircraft Co., Ltd.		
Dove	62	0.09
Piper Aircraft Corp.		
PA23, PA23160 (Apache)	1190	1.81
TEMCO Aircraft Corp.		
(Riley Twin Navion) D16, D16A	74	0.11
Multi-Engine Total	4442	6.76
SINGLE ENGINE:		
Aeronca Manufacturing Corp.		
058B[c]	137	0.21
11AC, 11BC, 11CC (Chief)[c]	1116	1.70
15AC (Sedan)[c]	262	0.40
65CA[c]	187	0.28
Beech Aircraft Corp.		
35, A35, B35, C35, D35, E35, F35, G35, H35, J35, (Bonanza)	4201	6.38
Bellanca Aircraft Corp.		
1413, 14132, 14133, 1419	317	0.48
14192 (Downer Aircraft Industries, Inc. and Northern Aircraft Inc.)	142	0.22
Boeing Airplane Co.		
A75, A75NI, B75NI, E75 (Stearman)[c]	1768	2.69
Cessna Aircraft Co.		
120, 140, 140A[c]	4170	6.34
150	100	0.15
170, 170A, 170B[c]	3237	4.92
172	2614	3.97
175	597	0.91
180, 180A, 180B	1874	2.85
182, 182A, 182B, 182C	2109	3.20
190, 195, 195A, 195B[c]	784	1.19
Champion Aircraft Corp.		
7AC, 7BCM, 7CCM, 7DC, 7EC, 7FC, 7GC (includes aircraft manufactured by Aeronca)	3816	5.80

TABLE 2.—*CONTINUED*

Manufacturer and Model (1)	Total Active Airplanes (2)	Percentage of Total Active Multi-and Single Engine Airplanes (3)
Single Engine (Continued):		
Forney Manufacturing Co.		
E, F, G, 415B, 415C, 415CD, 415D, 415F (includes Engineering and Research Corp. Ercoupe)	2513	3.82
Mooney Aircraft, Inc.		
M18C, M18C55, M18L, M18LA[c]	163	0.25
Mark 20, 20A	283	0.43
Piper Aircraft Corp.		
J3C65, J3F65, J3L65, J4a (Cub)		
PA-11[c]	4418	6.71
J5A, PA12[c]	1914	2.91
PA14, PA16[c]	582	0.88
PA15, PA17, PA18,		
PA18105 SPEC, PA18125, PA18135, PA18150		
PA18A, PA18A135 (Super Cub)	2064	3.14
PA18A150 (Agricultural applicator)	741	1.13
PA20, PA20135 (Pacer)		
PA22, PA22160, PA22135		
PA22150 (Tripacer)	5513	8.38
PA24, PA24250 (Comanche)	552	0.84
Silvaire Aircraft Co.		
(also airplanes manufactured by Luscombe)		
8A, 8B, 8C, 8E, 8F	2553	3.88
Taylorcraft, Inc.		
BC12D, BC12D1, BC1265, BC65	2325	3.53
BC65, DC065[c]		
Tusco, Corp. Navion Division		
(includes Navions by North American and Ryan)		
Navion, Navion A, Navion B[c]	1288	1.96
Universal Aircraft Industries		
Swift GC1A, GC1B[c] (includes airplanes manufactured by Globe and Temco)	690	1.05
Stinson 108, 1081, 1082, 1083[c] (includes aircraft manufactured by Convair and Piper)	2753	4.18
Single Engine Total	55783	84.78
Grand Total Multi- & Single Engine	60225	91.54

Calculation of Total Airplanes

Single engine (land)	60490
Multi-engine (land)	7222
Total	67712
Less aircarrier airplanes	-1899
Total active general aviation, land, single and multi-engine, airplanes as of January 1, 1959	65,813

[a] Less than 12,500 lb gross weight

[b] Source: U. S. Federal Aviation Agency, Statistical Study of U. S. Civil Aircraft, July, 1959

[c] No longer manufactured.

For the comparison of the effects of pressure altitude, temperature, and surface wind on runway length, the "basic" runway length for take-off was determined for the conditions 1 through 6; then each of the three factors was varied separately whereas the remaining five were held constant at the assumed conditions. The results of the effects of these three factors on runway length are shown in Fig. 1 as a percentage of the "basic" length. The surface wind effect is charted against a decrease in basic runway length whereas the others are for increases. In order to provide the reader with a knowledge of

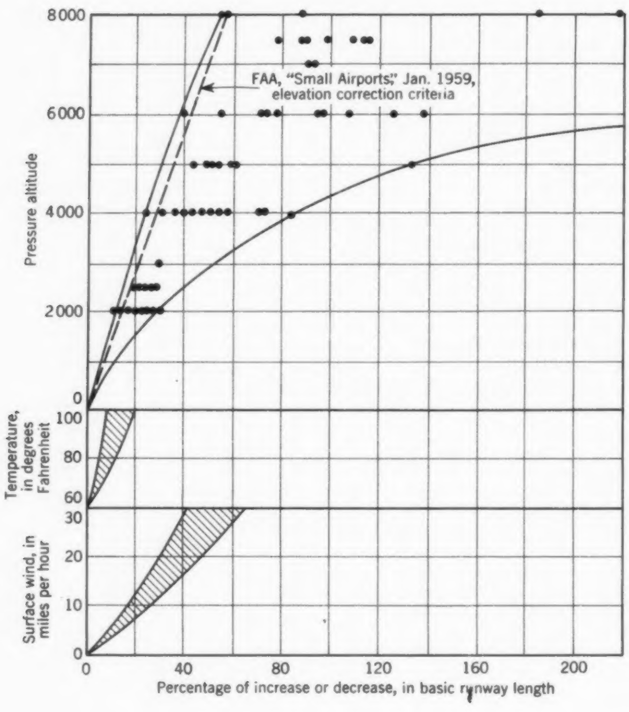

FIG. 1

the magnitude of runway lengths involved, the "basic" take-off distances for certain general aviation airplanes are listed in Table 3.

It can be seen from Fig. 1 that some of the airplanes included in this analysis have a wide performance variation and that some are very susceptible to the effects of pressure altitude. The airplanes used in this example are normal or utility category, single and multi-engine airplanes of gross weights less than 12,500 lb. The majority of the airplanes used in this example have a greater sensitivity of the effect of pressure altitude on take-off length than

does the 7% per 1,000 ft of elevation correction factor suggested by the FAA.[2] The engineer, therefore, should consider the performance characteristics of airplanes that may be using airports being developed at sites above sea level.

Temperatures above 60°F can also cause significant effects on runway length for this group of airplanes. At airport locations at which frequent high average daily temperatures are probable, the effect of temperature on performance should be considered in airport design.

Like pressure altitude, surface winds also have a major effect on runway length for take-off. Though the wind is important in the operation of an airplane, its variability makes it unsuitable as a runway design feature for a general aviation airport. The wind condition, therefore, should always be considered as zero for design purposes.

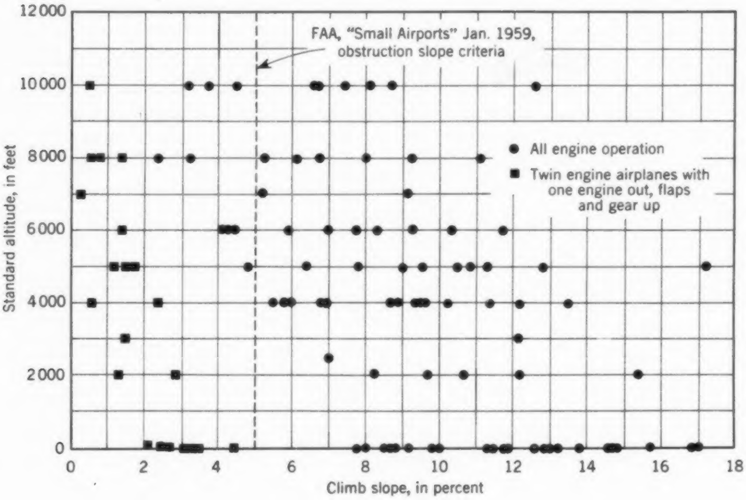

FIG. 2

Because the runway lengths for this group of airplanes are usually more critical for the take-off than for the landing, the landing conditions have not been included in this analysis.

It is important to note that the performance of the general aviation airplanes at take-off does not necessarily correlate to any one particular airplane feature, such as size or year of manufacture. As an example, a particular twin engine airplane, capable of carrying 7 people, with a maximum gross take-off weight of 9,300 lbs. At a pressure altitude of 3,000 ft and an air temperature of 80°F, this airplane requires 2,850 ft to reach a 50 ft height on take-off. Under the same altitude and temperature conditions, another airplane at 1,400 lb gross weight, and carrying 2 people, requires 3,250 ft; at

[2] Federal Aviation Agency, Small Airports, January, 1959, p. 12.

2,200 lf gross weight, another airplane carrying 4 people, requires 2,335 ft; another airplane at 4,830 lb gross weight, and carrying 5 people, requires 2,080 ft; and another airplane at 2,230 lb gross weight, and carrying 4 people, requires 3,100 ft. Whereas some of the aircraft included in this analysis are no longer manufactured, it should be noted that they still represent a large percentage of the active general aviation airplanes listed in Table 2.

TABLE 3.—TAKE-OFF DISTANCE FOR CERTAIN GENERAL AVIATION AIRPLANES[a]

Make	Model	Maximum gross weight, in pounds	Flap position	Take-off distance	
				Ground-roll, in feet	To 50 ft height, in feet
(1)	(2)	(3)	(4)	(5)	(6)
Aero Commander	680E	7500	1/4	-	1624(50°F) 1781(75°F)
Beechcraft	E18S	9300	0°	1950	2300
	J35	2900	0°	-	1350
	D50B	6300	20°	850	1180
	65	7700	0°	1309	1700
	95	4000	0°	1706	2080
Cessna	140A	1500	0°	588	1960
	150	1500	0°	680	1205
	170	2200	0°	728	1820
	172	2200	0°	725	1650
	175	2350	20°	735	1340
	182(1956)	2550	10°	570	990
	195(R755-9)	3350	0°	835	1670
	210	2900	20°	740	1135
	310	4600	15°	795	1405
	310C	4830	15°	800	1395
	310C	4830	0°	-	1576
Ercoupe	G	1400	-	-	2100
Navion	A	2750	0°	670	1500
	B	2850	0°	1030	1400
Piper	PA-18-95	1500	0°	390	750
	PA-18-150	1750	extended	200	500
	PA-22-150	2000	extended	1220	1600
	PA-22-160	2000	extended	1120	1480
	PA-23-160	3800	0°	1190	-
	PA-24-180	2550	0°	750	-
	PA-24-250	2800	0°	750	-
Stinson	1082	2230	0°	-	1900
	1083	2400	0°	-	2313(50°F) 2545(75°F)

[a] Conditions: Sea level, standard atmospheric conditions; zero wind; level, hard surface runway; maximum gross take-off weight.

Climb Slope.—Not only is the airport design affected by the performance of the airplane during take-off, but it is also indirectly affected by the airplane's climbing performance in the air. The provision of a runway of sufficient length for a safe take-off is of little advantage if a natural or man-made obstruction in the flight path is too high.

The Federal government and many local agencies have recognized the problem created by obstructions, either man-made or natural. The FAA has established standards for determining what constitutes an obstruction[3] and has recommedned approach protection methods.[4] Many state, county, and city governments have provided zoning or purchased land rights to provide their airports protection from obstruction encroachment.

To further aid in the knowledge of obstruction determination, the demonstrated climbing capabilities of the airplanes previously mentioned have been compiled. Based on the best rate of climb speed (TAS) and the maximum rate of climb at gross weight, the approximate climb slope (as a percentage) is indicated in Fig. 2 for each airplane at various standard altitudes. Standard altitude is defined as an elevation in a standard atmosphere, in which the atmospheric pressure and temperature are standard, based upon defined lapse rates from the sea level standard condition of 29.92 inches of mercury atmospheric pressure and 59°F atmospheric temperature.

It can be seen that the 20:1 (5%) obstruction slope criteria suggested by the FAA for small airports[5] provides an excellent safety clearance, for the airplanes considered, up to a standard altitude of 2,500 ft. Above 2,500 ft, however, this margin of safety rapidly diminishes until, at 5,000 ft standard altitude, it has vanished for several of the airplane types. Again, the performance of the airplanes using the small airport must be considered to safety evaluate the airport approach zone requirements.

Many of the light twin-engine airplanes do not have engine failure take-off performance at maximum gross weight. They are capable, however, of a positive climb slope if an engine failute occurs after take-off. These engine-out climb slopes are also shown in Fig. 2. These slopes are usually too restrictive to be considered as a design guide.

SUMMARY

It has been demonstrated how actual airplane performance may vary widely between airplanes through various atmospheric pressure and temperature ranges, and how these variations may have a significant effect on runway length and determination of airport obstructions. This presentation has been made to offer the designer a method of selecting runway lengths and obstruction clearances for small airports that serve general aviation airplanes. This method recommends an appraisal of the performance of the using vehicles for the conditions that may be expected to exist at the airport site.

The performance characteristics of the airplanes considered in this analysis are sufficiently sensitive so that these characteristics should be considered in the design of general aviation airports. To accomplish this, it is necessary that not only the pilot, but also the airport designer, have knowledge of airplane performance. Because the lighter airplanes are often critical from

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[3] Federal Aviation Agency, TSO-N-18-1, Standards for Determining Obstructions to Air Navigation, July, 1952.

[4] Civ. Aeronautics Administration (FAA), CAA Policy on Runway Clear Zones, July 1, 1957.

[5] Federal Aviation Agency, TSO-N-18-1, Standards for Determining Obstructions to Air Navigation.

the airport design standpoint, the Civil Air Regulations, Part 3, for determination and publication of take-off, landing, and climb performance data should be required for all airplanes, not just those above a certain weight categrory. This would assure sufficient knowledge for safe operation by the pilot and safe design by the engineer.

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RUNWAY ROUGHNESS STUDIES IN THE AERONAUTICAL FIELD

By John C. Houbolt[1]

SYNOPSIS

Attention is given to several phases of the runway roughness problem as it affects the operation of airplanes. Means for measuring roughness, and the manner of analyzing and presenting data so as to best indicate the nature of characteristics of the roughness, are presented. Various types of criteria for smoothness are then considered for new construction and as a guide for determining when repairs are necessary.

Theoretical and experimental studies are also presented which deal with means for predicting the loads that develop in the airplane structure during taxiing. In this connection, available statistical loads data gathered during routine taxi operation of aircraft are reviewed.

Note.—Discussion open until August 1, 1961. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Air Transport Division, Proceedings of the American Society of Civil Engineers, Vol. 87, No. AT 1, March, 1961.

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INTRODUCTION

A number of studies have been made of the runway roughness problems that are encountered in the operation of airplanes.[2,3,4,5,6,7] The purpose of this paper is to review the results of some of these studies for the benefit of those civil engineers concerned with road construction or road roughness problems. Specifically, four aspects are considered: (1) the means for measuring runway roughness; (2) the analysis and form for presenting roughness data; (3) the consideration of criteria for establishing limits of acceptable roughness; and (4) studies of the loads developed in aircraft during taxiing operations.

Runway roughness constitutes a problem to aircraft designers and operators which has grown in severity. Reasons for concern about the problem are as follows:

1. Structural failure of certain large aircraft carrying external stores.
2. Concern of designers that the fatigue life of the structure is being reduced.
3. Difficulty in reading panel instruments.
4. Pilot reports of severe roughness.
5. Undocumented complaints by both pilot and travellers of a rough ride.

The problem affects designers, operators, passengers, and runway builders.

With regard to the growth in the severity of the problem, three major causes may be cited: (a) the increased use of large masses such as engines, tanks, and missiles on the outboard regions of the wing; (b) the use of higher pressure tires; and (c) increased taxiing speeds. Although increased taxi speeds tend to aggravate roughness problems in general, roughness troubles may occur at all taxi speeds, for example, the traversing of a washboard type road at just the right speed to produce severe undulations.

USE OF POWER SPECTRAL TECHNIQUES

There is frequent reference to a power spectral approach throughout this paper. This approach may not as yet be fully disseminated throughout the civil

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[2] "Some Measurements and Power Spectra of Runway Roughness," by James H. Walls, John C. Houbolt, and Harry Press, NACA TN 3305, November, 1954.

[3] "On Spectral Analysis of Runway Roughness and Loads Developed During Taxiing," by John C. Houbolt, James A. Walls, and Robert F. Smiley, NACA TN 3484, July, 1955.

[4] "Measurements of Runway Roughness of Four Commercial Airports," by Dexter M. Potter, NACA RM L56126, January, 1957.

[5] "Measurements and Power Spectra of Runway Roughness at Airports in Countries of the North Atlantic Treaty Organization," by Wilbur E. Thompson, NACA TN 4303, July, 1958.

[6] "Study of Taxiing Problems Associated with Runway Roughness," by Benjamin Milwitzky, NASA MEMO 2-21-59L, March, 1959.

[7] "Progress and Recommended Research Activity on the Runway Roughness Problem," by John C. Houbolt, presented at the Structures and Materials Panel, AGARD, NATO Meeting, Copenhagen, Denmark, October 20 to 29, 1958.

engineering profession. Therefore, a review is given of the basic concepts involved in this approach.[8,9]

Assume that the elevation profile along a line down a runway is known. If this profile were analyzed by Fourier series methods for the amplitudes a_n of the sine terms and the amplitudes b_n of the cosine terms, then a plot of $c_n^2 = a_n^2 + b_n^2$ may be made, as shown in Fig. 1(a). The height of the columns gives a direct indication of the extent to which each discrete frequency component appears in the Fourier series analysis. (The square of the amplitude is used so as to be analogous with the spectral results to be presented subsequently.)

In the spectral approach (Appendix) all frequency components appear, and not just discrete even multiples of a fundamental frequency. The spectrum values make a plot of the type shown in Fig. 1(b). Effectively, the Dirac columns of Fig. 1(a) are smeared out by the spectrum approach to yield the continuous curve of Fig. 1(b). Thus, the value of $\phi(\Omega)$ indicates the roughness power contained between a frequency Ω and the $\Omega + d\Omega$, just as the c_n^2 indicates the power at the frequency Ω_n. A concise picture of roughness makeup of the given random profile is thus given by the power spectrum. This spectrum also contains additional information about the profile. For example, the area under the spectrum curve equals the mean-square value of the elevation values of the given profile. Other properties, such as number of peaks above a given level of elevation, number of crossings at a given level, and others, are presented elsewhere.[8,9]

Assume a system rolls along the profile, as shown in Fig. 2(a). If the system has linear response characteristics, then the power spectrum for the response of the system to the roughness can be predicted rather easily as shown in Fig. 2(b). Fig. 2(b1) is the spectrum of elevation values, as mentioned previously. Fig. 2(b2) is the system transfer function, and specifically indicates the square of the amplitude of the response of the system due to rolling over a sinusoidal curve of frequency Ω and of unit amplitude (that is, the square of the frequency response function). Through this function, all the response characteristics of the system, resonant or otherwise, are taken into account. The power spectrum of the response of the system to the given profile follows directly by multiplying these two curves together, Fig. 2(b3). The area under this response spectrum is equal to the mean-square value of the response, etc. Note that in this particular application, where distances are involved, it is appropriate to work in terms of the spacial frequency Ω. In other applications the circular frequency ω may be more convenient. The interdependence of these frequency and associated power spectra is examined in the Appendix.

Sketches of the type given in Fig. 2 can also be used to explain how the response is influenced by various factors such as different rolling speeds, different damping, or the presence of peaks in the input spectrum (Fig. 3). Consider first the use of two different values of damping in the system, the lower value of damping might lead, for example, to the transfer function labeled A, whereas the higher damping would give the curve B. It follows that the output

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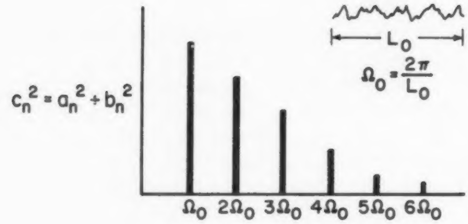
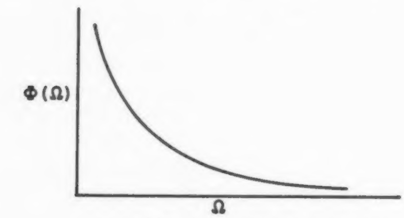
8 "Some Applications of Generalized Harmonic Analysis to Gust Loads on Airplanes," by Harry Press and John C. Houbolt, Journal of the Aeronautical Sciences, Vol. 22, No. 1, January, 1955.

9 "Power Spectral Methods of Analysis and Application in Airplane Dynamics," by H. Press and J. W. Tukey, Bell Telephone System Tech. Publication, Monograph 2606, June, 1956.



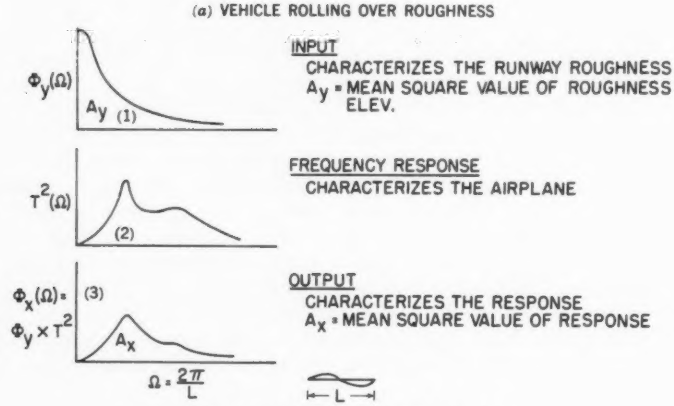
(*a*) FOURIER SERIES APPROACH



(*b*) POWER SPECTRUM APPROACH

FIG. 1.—ROUGHNESS ANALYSES

(*a*) VEHICLE ROLLING OVER ROUGHNESS



(*b*) POWER SPECTRAL ANALYSIS FOR RESPONSE

FIG. 2.—VEHICLE RESPONSE TO ROUGHNESS BY POWER SPECTRAL MEANS

spectrum for case A encloses more area than in case B, and hence, the mean-square value of response would be greater for case A. The influence of damping on the response is thus seen. Speed effects are brought out by the two curves designated by 20 mph (B) and 40 mph. Changing the speed of rolling is seen to stretch or shorten the transfer curve (the effect of v on the frequency argument is brought out in the Appendix). Since increasing the speed shifts the transfer function to regions of higher input spectrum, the output spectrum will in general exhibit greater area and indicate a greater mean-square value of response. Consider the situation where the input spectrum exhibits a pro-

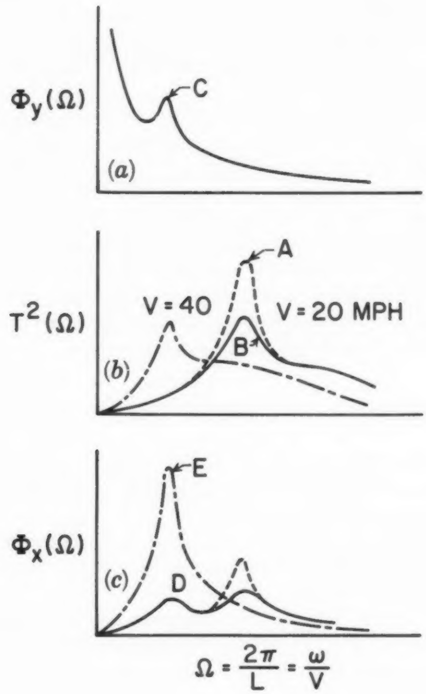


FIG. 3.—EFFECTS OF INPUT PEAKS, DAMPING, AND VELOCITY

nounced peak, as in the case when there is a fairly large concentration of roughness having a substantially constant wave length (peak C in Fig. 3(a)). This peak will, of course, carry through to the output (D). If any peak in the transfer function shifts under this input peak by virtue of a change in speed, then an appreciable reinforcement will occur and will lead to a sizable peak in the output response (E). The condition of riding over a washboard road at a speed which excites vehicle resonance is a good example of this case.

Thus, from Fig. 3, some of the advantages that are offered in analyzing runway roughness by a spectral approach are seen. Not only does the spectrum give a concise picture of the makeup of the roughness, but it tells which wave lengths contribute most to the roughness. The qualitative and quantitative behavior of a vehicle rolling over the roughness is readily predicted.

MEANS FOR MEASURING ROUGHNESS

Some of the means that have been used, or might be used, for measuring runway roughness will be described. The apparent lack of cognizance of numerous devices used in road roughness studies (profilometers, profilgraphs, etc.) may seem conspicuous, but no slight is intended. Generally these devices provide a good index of roughness, but the results are not of a form which makes load studies feasible, which was one of the original objectives in the aircraft studies.

Of the methods to be presented, the transit and rod method, taking elevation readings every 2 ft along a runway line, has proven a simple and most productive means for measuring runway roughness. To date (1961), 60 runways have been measured in the United States and Europe.[2,3,4,5]

A cart method for measuring runway elevations by means of a light beam is described elsewhere.[10] Other cart methods for measuring roughness are depicted in Figs. 4. Figs. 4(a) and (b) measure runway roughness properties directly, and an analysis of the slope measuring cart is given in the Appendix. Figs. 4(c) and (d) give an indirect measure of roughness through the response the roughness produces in an airplane or a drawn cart.

PRESENTATION OF ROUGHNESS DATA

Of the many ways for presenting roughness data, four are worthy of note.

1. Actual elevation profiles, as for example the representative portions of four different runways shown in Fig. 5.

2. Power spectra of runway elevations, Fig. 6, in which ϕ, the power spectrum, is plotted against the spacial frequency Ω, which is related to the wave length L of the frequency components by $\Omega = 2\,\pi/L$.

3. Acceleration response that is experienced in an airplane during actual taxiing at various speeds (Fig. 7). The curves are theoretically derived and will be examined later. The solid points were obtained in taxiing tests of the F-100 on runway "X."

4. Maximum departure from a straight edge placed on the runway surface (Fig. 10 illustrating this type presentation will be given subsequently).

CRITERIA FOR ROUGHNESS

With each of the four means mentioned in the preceding section for presenting runway roughness, criteria may be developed for establishing smoothness standards to be met in the construction of new runways or in judging when

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10 "Development of a Method and Instrumentation for Evaluation of Runway Roughness Effects on Military Aircraft," by C. K. Grimes, WADC Report, AGARD, January, 1957.

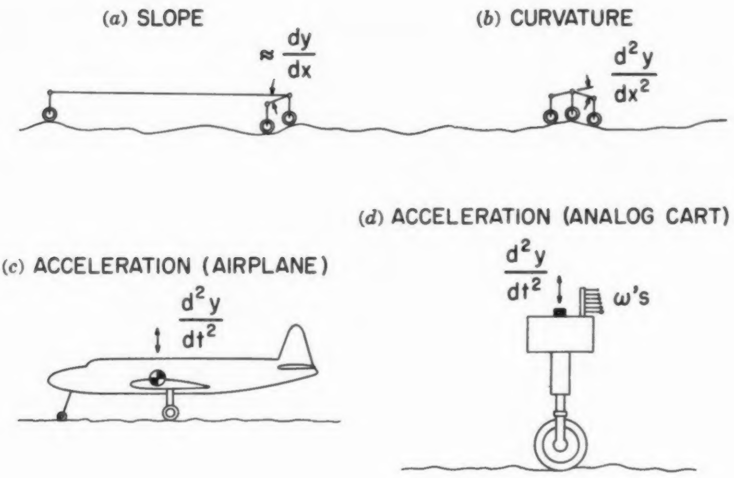

FIG. 4.—ROUGHNESS CARTS

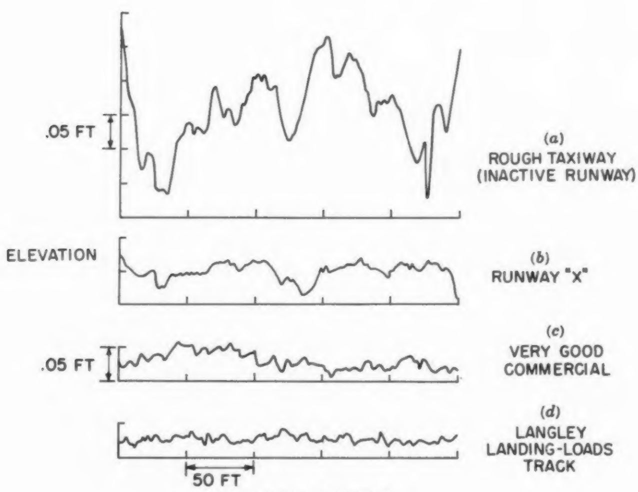

FIG. 5.—REPRESENTATIVE RUNWAY ELEVATION PROFILES

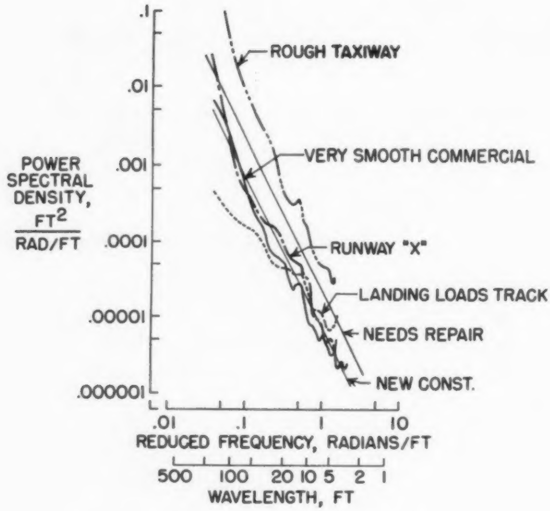

FIG. 6.—TYPICAL SPECTRA OF RUNWAY ELEVATION

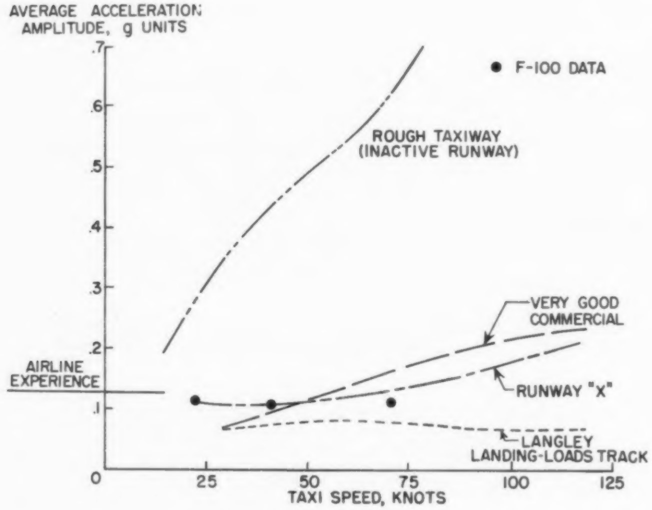

FIG. 7.—EFFECT OF TAXI SPEED ON ACCELERATION

repairs are necessary (Fig. 8). (Some of the numerical values that are referred to have been changed slightly from the values indicated elsewhere.[6,7])

1. For the profile scheme of Fig. 5, the roughness should not fall outside a certain band width in a certain length (Fig. 8(a)). The curves in Figs. 5(a) and (d) represent the upper and lower extremes in roughness encountered in the runway that have been measured. The roughness of the curves in Figs. 5(c) and (d) is known to be quite acceptable. Runway "X," however, is just on the verge of becoming a borderline case, for most operations it appears good, but occasionally complaints of roughness have been made. A runway with greater elevation deviations, such as the curve in Fig. 5(a), would therefore be judged as too rough.

2. For the power spectrum scheme of Fig. 6, upper limits of the spectrum may be stipulated (Fig. 8(b)). This limit as well as a new construction limit are shown in Fig. 9 in relation to the power spectra curves of Fig. 6. As mentioned previously, the main advantage of the spectral approach is that it gives a concise picture of the detailed makeup of the roughness, and pinpoints the wave lengths that are troublesome.

3. For the acceleration approach of Fig. 7, an upper limit on acceleration may be set (Fig. 8(d)). Not enough information exists to set this limit, but indications are that the upper bound for the average value of the peak accelerations should be in the neighborhood of 0.3 g.

4. For the straight-edge approach, maximum deviations from a straight edge of varying length may be stipulated (Fig. 8(c)). The average deviations from a straight edge have been deduced from the four runways of Fig. 5, and are shown in Fig. 10, together with suggested criteria values shown by solid points. To insure that longer wave-length roughness does not appear, it is essential that allowable deviations be specified for large L's, not just the L's in the order of 10 ft, as is commonly done.

AIRPLANE EXPERIENCE

Studies of many VGH records from airplane operations show that:

1. The amount of time spent in taxiing is remarkably constant at about 5 min per flight (a flight meaning one departure and one arrival).

2. Significantly, about 80% of this 5 min is spent on taxiways.

3. For a wide range of airplanes, including fighters, transports, and heavy bombers, the predominant response of the landing gear occurs in a narrow frequency range between 1.5 and 2 cycles per sec. Taxiways are usually much rougher than runways, and since 80% of the taxi time is spent on the taxiways, it would appear that they are the major contributors to fatigue troubles due to taxiing, if any exist. It would be of little help to improve runways to correct fatigue troubles unless taxiways are similarly improved.

Fig. 11 is a statistical presentation showing spread and mean values of the number of acceleration peaks that have been found to exceed various values of acceleration in the analysis of many VGH records. The average acceleration peak is 0.12 g.

COMPUTATION STUDIES OF AIRPLANE RESPONSE

Analytical studies of airplane response due to taxiing can be made by three approaches: (a) digital, (b) analog, and (c) power spectral. The digital and

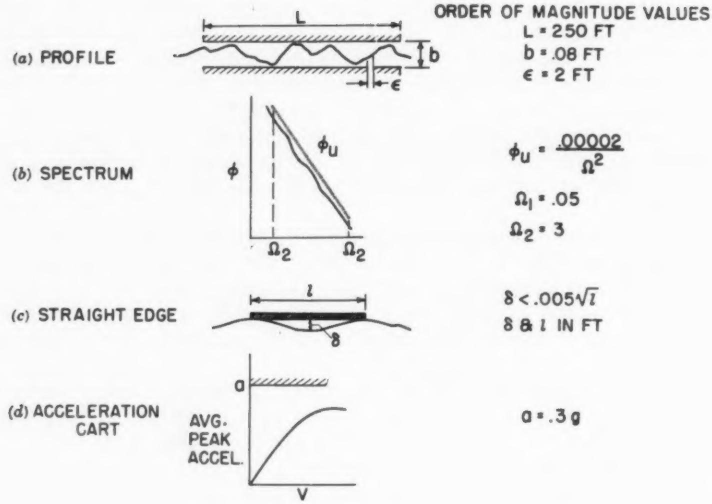

FIG. 8.—TOO ROUGH, ROUGHNESS CRITERIA

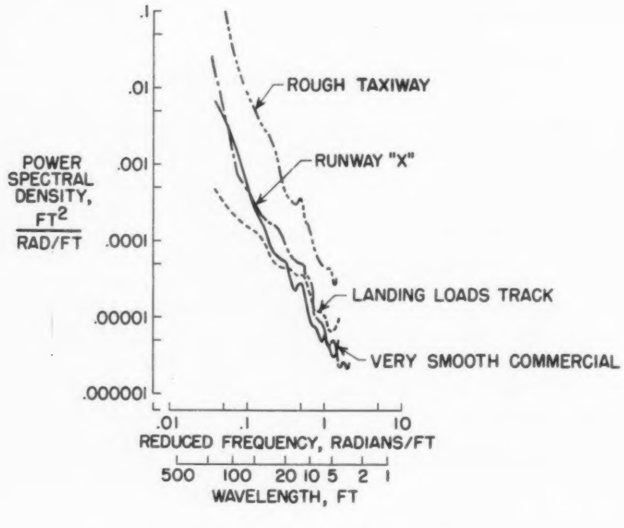

FIG. 9.—LIMITING SPECTRAL CRITERIA

analog approaches are considered to yield good answers, but solution is time consuming and much work is required to obtain results having a statistical significance. The power spectral approach is intended to cut down on the effort required. Results obtained so far show that no unique transfer function exists for the highly nonlinear landing-gear systems that are used on airplanes. The idea being pursued, therefore, is to try to arrive at a near equivalent linear system. Analytical studies show a characteristic response frequency of from 1.5 to 2.0 cycles per sec, in agreement with the value found in actual airplane operation. The approach appears useful for evaluating trends such as brought about by mass changes and for pinpointing conditions that should be avoided.

The curves of Fig. 7 apply to the assumed taxiing of the F-100 airplane over the four runways of Fig. 5, and were computed through use of the concept that

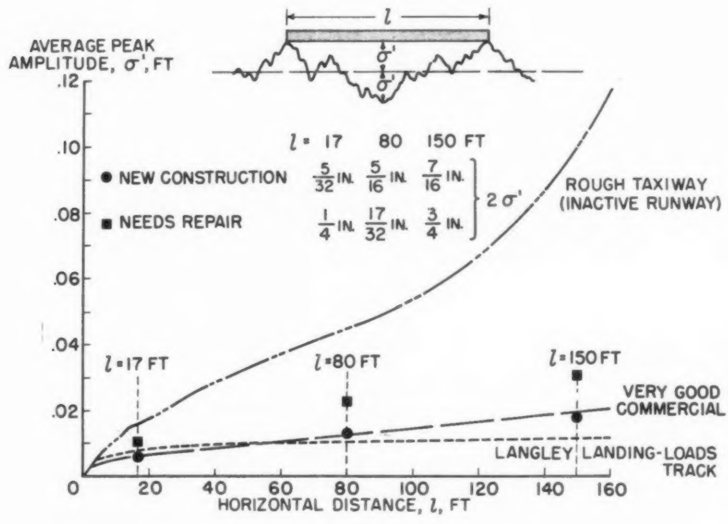

FIG. 10.—AVERAGE ROUGHNESS AMPLITUDE

an effective linear transfer function may be used. The solid points were obtained in actual taxiing tests of the F-100 over runway "X," and correlate well with the computed values. As a matter of comparison, the average acceleration value of 0.12 g found in airline operation is shown also in Fig. 7.

SOME SEQUEL MEASUREMENTS

Fig. 12 represents an interesting compilation made after the spectral criteria presented in Fig. 9 were deduced. The three runways shown in Fig. 12 are different than those mentioned heretofore. If the elevation profiles in Fig.

12(b) are judged from the runway roughness levels mentioned previously in connection with Figs. 5 and 8, then it would appear that the bottom runway is satisfactorily smooth, but that the top two are not. This is substantiated further in Fig. 12(a), where the spectra of roughness are compared with the two suggested limiting spectra criteria. The spectrum for the good runway falls almost wholly below the criteria. (The lower values of Ω is Fig. 12(a) should be discounted, since they correspond to wave lengths longer than those which cause airplane response trouble.) The spectrum for the middle runway crosses the criteria, indicating good characteristics for short wave lengths, but poor characteristics at long wave lengths. The top rough runway has a spectrum which lies wholly above the criteria. (Note that this runway is an unprepared field.)

The profile in Fig. 13(b) is a theoretical profile made by constructing a curve to have the maximum deviations that are allowed by an existing specifi-

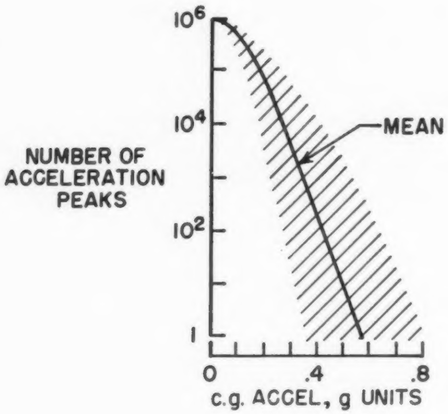

FIG. 11.—DISTRIBUTION OF TAXIING LOADS PER 1,000 FLIGHTS

cation for runway smoothness. From an elevation deviation point of view, remembering Figs. 5 and 8, it appears too rough. This is verified by the associated spectrum in Fig. 13(a). Again the runway has good short-wave-length characteristics, but is poor at the longer wave lengths.

CONCLUSIONS

The results of several studies dealing with runway roughness problems have been summarized. The aim has been principally to touch on the concepts that are involved, such as the means for obtaining roughness data, the suggested forms for smoothness criteria, and the means for predicting the loads that are developed during taxiing. The use of power spectral concepts has been outlined in detail, because of the newness of this approach to this particular field.

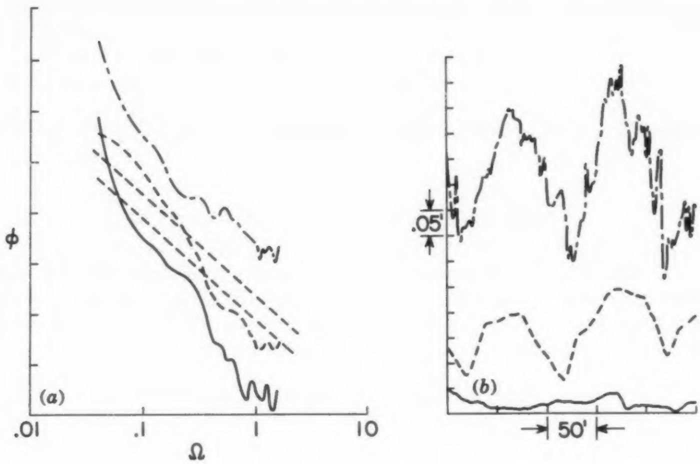

FIG. 12.—PROFILE AND SPECTRA EXTREMES

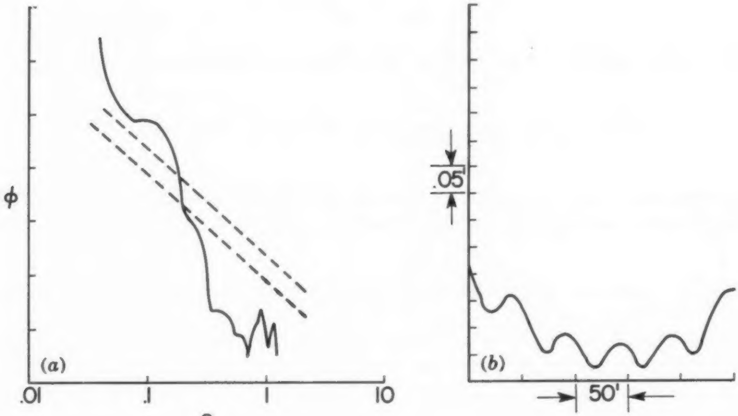

FIG. 13.—THEORETICAL PROFILE AND SPECTRUM

The roughness treated herein is that of the continuous type. Taxiing over discrete bumps such as chuck holes or running off the edge of the pavement are conditions distinct and separate enough to require a different treatment from that given.

APPENDIX.—POWER SPECTRAL CONSIDERATIONS OF ROUGHNESS

DEFINITION OF ROUGHNESS SPECTRUM

Consider that the elevation measurements along a runway line are a measure of roughness and designate these elevations as y(x) in the interval of x extending from -X to X. The power spectrum of these elevations is then defined by the equivalent relations

$$\phi(\Omega) = \lim_{X \to \infty} \frac{1}{2 \pi X} F(\Omega)\ F(-\Omega)$$

$$= \frac{1}{\pi} \int_{-\infty}^{\infty} R(x) e^{-i\Omega x}\ dx = \frac{2}{\pi} \int_{0}^{\infty} R(x) \cos(\Omega x)\ dx \qquad (1)$$

in which $F(\Omega)$ is in the nature of a truncated Fourier transform defined by

$$F(\Omega) = \int_{-X}^{X} y(x) e^{-i\Omega x}\ dx \qquad (2)$$

and $R(x)$ is the autocorrelation function of the elevations

$$R(x) = \lim_{X \to \infty} \frac{1}{2X} \int_{-X}^{X} y(\eta)\ y(\eta + x)\ d\eta \qquad (3)$$

The meaning of the frequency argument Ω can be brought out by reference to a simple sine wave having a wave length L, as follows:

$$\sin \frac{2 \pi x}{L} = \sin(\Omega x) \qquad (4)$$

Hence, Ω is in the nature of a spacial frequency defined by $\Omega = 2\pi/L$. In the case where the behavior of a vehicle travelling over the runway at a given velocity is being considered, a circular frequency is introduced. This can be illustrated by again referring to a sine wave, thus

$$\sin \frac{2 \pi x}{L} = \sin(\Omega x) = \sin(\Omega v t) = \sin(\omega t) \qquad (5)$$

Hence, the relationship that exists between the frequencies, velocity, and wave length are

$$\omega = \Omega v = \frac{2\pi}{L} v \qquad (6)$$

The power spectra involving the arguments Ω and ω can be shown to be related by $\phi(\Omega) = v\,\phi(\omega)$.

In the numerical treatment of runway profiles by direct application of Eqs. 1 and 3, some errors may arise because an effective filtering action causes the large values of the power spectrum that are usually found at the low values of Ω (large wave lengths) to leak through and distort the values at high Ω. This situation can be avoided by use of a so-called pre-whitening technique. For runways, one technique that has been used is as follows: (1) form the new function

$$Y(x) = y(x) - y(x - \epsilon) \quad \ldots \ldots \quad (7)$$

in which ϵ is distance between successive elevation measurements (commonly taken as 2 ft); (2) determine the power spectrum of $Y(x)$; and (3) correct this power spectrum by the appropriate post-darkening function to arrive at the power spectrum of $y(x)$. The post-darkening function associated with Eq. 7 is derived as follows: The Fourier transform of Eq. 7 is

$$F_Y(\Omega) = \int_{-X}^{X} y(x) e^{-i\Omega x}\, dx - \int_{-X}^{X} y(x - \epsilon) e^{-i\Omega x}\, dx$$

$$= F_y(\Omega) - e^{-i\Omega\epsilon} F_y(\Omega) \quad \ldots \ldots \quad (8)$$

from which the power spectrum of Y follows as

$$\phi_Y(\Omega) = \lim_{X\to\infty} \frac{1}{2\pi X} F_Y(\Omega)\, F_Y(-\Omega)$$

$$= \left(1 - e^{-i\Omega\epsilon}\right)\left(1 - e^{-i\Omega\epsilon}\right) \lim_{X\to\infty} \frac{1}{2\pi X} F_y(\Omega)\, F_y(-\Omega)$$

$$= 2(1 - \cos \Omega\epsilon)\, \phi_y(\Omega) \quad \ldots \ldots \quad (9)$$

From Eq. 9 it follows that $\phi_y(\Omega)$ is

$$\phi_y(\Omega) = \frac{1}{2(1 - \cos \Omega\epsilon)}\, \phi_Y(\Omega) \quad \ldots \ldots \quad (10)$$

in which the factor multiplying ϕ_Y is the post-darkening function. Further information on the actual details of the numerical procedure that has been used to evaluate power spectra of runway roughness is given elsewhere.[5]

ANALYSIS OF A SLOPE MEASURING CART

The measurement taken by a cart of the type shown in Fig. 4(a), while not indicating slope exactly, can nevertheless be analyzed to yield the power spectrum of runway elevations. Specifically, suppose the cart were as shown in Fig. 14. The measurement α would be

$$\alpha = \frac{1}{\epsilon_1}\left[y(x) - y\left(x - \epsilon_1\right)\right] - \frac{1}{\epsilon_2}\left[y(x) - y\left(x - \epsilon_2\right)\right] \quad \ldots \ldots (11)$$

Its Fourier transform would be

$$F_\alpha(\Omega) = \frac{1}{\epsilon_1}\left(F_y - e^{-i\Omega\epsilon_1} F_y\right) - \frac{1}{\epsilon_2}\left(F_y - e^{-i\Omega\epsilon_2} F_y\right)$$

$$= \left[\left(\frac{1}{\epsilon_1} - \frac{1}{\epsilon_2}\right) - \frac{1}{\epsilon_1} e^{-i\Omega\epsilon_1} + \frac{1}{\epsilon_2} e^{-i\Omega\epsilon_2}\right] F_y(\Omega) \quad \ldots\ldots\ldots (12)$$

which by Eq. 1 would, in turn, lead to the power spectrum for α as

$$\phi_\alpha(\Omega) = \Bigg[\left(\frac{1}{\epsilon_1} - \frac{1}{\epsilon_2}\right)^2 + \frac{1}{\epsilon_1^2} + \frac{1}{\epsilon_2^2} - \frac{2}{\epsilon_1}\left(\frac{1}{\epsilon_1} - \frac{1}{\epsilon_2}\right)\cos\Omega\,\epsilon_1$$

$$+ \frac{2}{\epsilon_2}\left(\frac{1}{\epsilon_1} - \frac{1}{\epsilon_2}\right)\cos\Omega\,\epsilon_2 - 2\frac{1}{\epsilon_1}\frac{1}{\epsilon_2}\cos\Omega\left(\epsilon_2 - \epsilon_1\right)\Bigg] \quad \ldots\ldots (13)$$

For the case of $\epsilon_2 = 11\,\epsilon_1$ Eq. 13 becomes

$$\phi_\alpha(\Omega) = \frac{1}{\epsilon_1^2}\Big[1.835 - 1.818\,\cos\left(\Omega\,\epsilon_1\right) + 0.165\,\cos\left(11\,\Omega\,\epsilon_1\right)$$

$$- 0.182\,\left(\cos 10\,\Omega\epsilon_1\right)\Big]\,\phi_y(\Omega) = \frac{1}{\epsilon_1^2}\,L(\Omega)\,\phi_y(\Omega) \quad \ldots (14a)$$

Thus

$$\phi_y(\Omega) = \frac{\epsilon_1^2}{L(\Omega)}\,\phi_\alpha(\Omega) \quad \ldots\ldots\ldots\ldots\ldots\ldots (14b)$$

In reviewing the significance of Eqs. 14(a) and (b) it should be noted first that relative to Eq. 7, Eq. 11 represents another type of pre-whitening that is

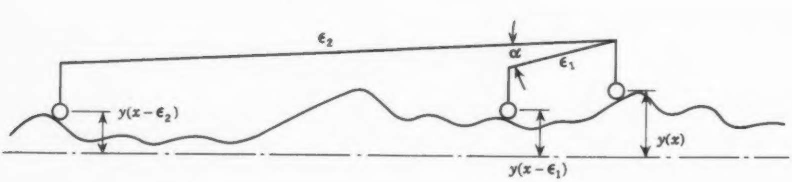

FIG. 14

applied to the elevation values. The quantity $\frac{\epsilon_1^2}{L(\Omega)}$ in Eq. 14(b) represents the post-darkening factor that must be applied to $\phi_\alpha(\Omega)$ to yield the spectrum of elevations. The factor $L(\Omega)$ is shown in Fig. 15; except for the high-frequency component, it is quite similar to the corresponding factor, $2(1 - \cos\Omega\,\epsilon)$, in

Eq. 10. If ϵ_2 were larger, then $L(\Omega)$ would reduce to the simpler form contained in Eq. 10.

ROUGHNESS DEVIATIONS FROM A STRAIGHT EDGE

By integration under the spectrum.—Consider that the profile curve of a runway is such that it represents deviations from a mean straight line, as shown in Fig. 16. The power spectrum of the deviations then generally appear as seen in Fig. 17. The rectangular scales have been used instead of the log-

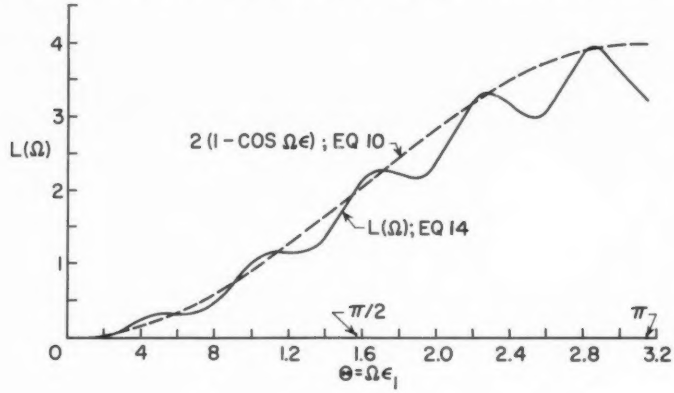

FIG. 15.—POST-DARKENING FUNCTIONS

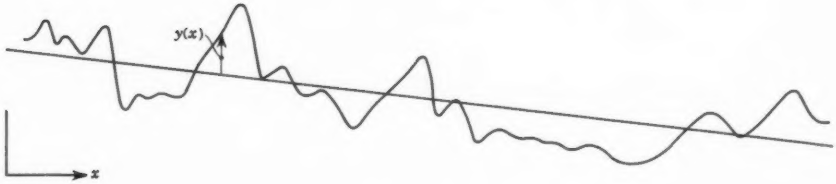

FIG. 16

log scales generally used, and Ω is the spacial frequency associated with the frequency component having a wave length L.

One of the useful properties of the spectrum is that the area under the curve is equal to the mean-square value of the runway deviations. It is also true that the area between Ω_1 and ∞ (Fig. 17) is associated with the mean-square value of the deviations that are contained within a runway segment of length $L_1 = 2\,\pi/\Omega_1$. This last statement is the key to the present deviation.

Suppose the spectrum is represented by the curve

$$\phi(\Omega) = \frac{c}{\Omega^n} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

The mean-square value of roughness that is present in a length L_1 is then

$$\sigma^2 = \int_{\Omega_1 = \frac{2\pi}{L_1}}^{\infty} \frac{c}{\Omega^n}\, d\Omega = \frac{c}{n-1}\left(\frac{L_1}{2\pi}\right)^{n-1} \quad \ldots\ldots\ldots\ldots (16)$$

which gives a root-mean-square value of

$$\sigma = \left(\frac{c}{n-1}\right)^{1/2}\left(\frac{L_1}{2\pi}\right)^{\frac{n-1}{2}} \quad \ldots\ldots\ldots\ldots (17)$$

In actual practice, values of the spectrum are not usually determined beyond a value of $\Omega = \pi/2$, which corresponds to a wave length L of 4 ft (at least two points per cycle are necessary to discern a periodic wave, and for the commonly used measurement spacing of 2 ft, this would correspond to a minimum

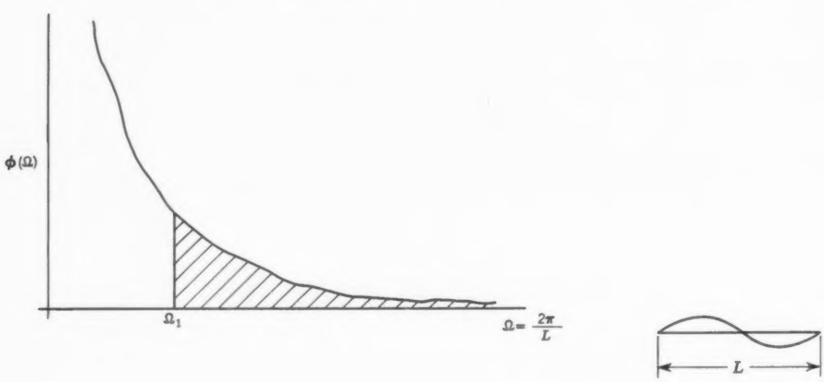

FIG. 17

discernable wave length of 4 ft). The amount of area found beneath the spectrum beyond the frequency of $\pi/2$ is so small, however, that it may be neglected, and thus whether the upper limit is finite or infinity is immaterial.

The root-mean-square value of the roughness deviations about a mean line in length L_1 has thus been found, but the maximum deviation in this length still remains to be determined. Random process theory shows that the maximum value σ' can be given as

$$\sigma' = k\,\sigma \quad \ldots\ldots\ldots\ldots (18)$$

in which k is to be regarded as a form factor which depends on the nature of the roughness. Experience shows that the value of k is in the neighborhood of the value for a pure sine wave, that is, $k = \sqrt{2}$ and this value is adopted herein.

Thus

$$\sigma' = \sqrt{2}\ \sigma = \sqrt{2}\left(\frac{c}{n - 1}\right)^{1/2}\left(\frac{L_1}{2\ \pi}\right)^{\frac{n-1}{2}} \quad \ldots\ldots\ldots \quad (19)$$

This equation is now regarded as a criterion for smoothness. To obtain numerical values, it is necessary to assign values to c and n. This is done by fitting the assumed spectrum Eq. 15 to the spectrum of runways of which information is known. For example, take the very good commercial runway indicated in Fig. 6. This runway was judged to be an example of a good runway, and was known to have been carefully constructed according to certain specifications. The position taken, therefore, was that if this is a good runway and was built according to certain construction standards, then it should serve as a model for the construction of all new runways. Thus, the dashed curve for new construction shown in Fig. 9 was obtained substantially by using the very good commercial runway as a criterion. Values of c and n for this curve are $c = 0.0000067$ and $n = 2.0$. This yields

$$\sigma' = 0.00146\ \sqrt{L} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (20)$$

in which σ' and L are in ft, and the subscript on the L has been dropped.

The solid circles shown in Fig. 10 follow esentially from Eq. 20, with some rounding off. The curves shown in Fig. 10 were derived by actual numerical

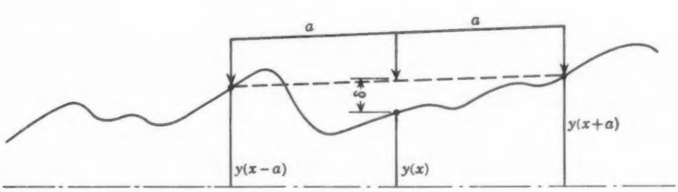

FIG. 18

integration under the spectra. The solid circular points, as derived on the basis of an idealized spectral shape, are in good agreement with the numerical results for the very good commercial runway, on which the idealized shape was based.

Regarding the needs repair criterion, it was reasoned that the limiting spectrum should fall somewhere between the good acceptable runways and the rough taxiway which was known by experience to be too rough for landing and take-off operation. The establishment of the level of the spectrum was also aided by experience gained from operation on runway "X." This runway, although on the whole fairly good, was found to lead to occasional complaints during certain types of operation. Response studies indicated that these complaints could be associated with the rise in the spectrum for wave lengths in the order of 10 ft

to 20 ft (Fig. 6). It was felt then that a level of acceptable roughness would be just above the runway "X" values. The needs repair criterion was, therefore, drawn to pass slightly above the spectrum for runway "X" and was arbitrarily made parallel to the new construction criterion. Somewhat fortuitously, the roughness deviations that were found to be associated with this spectrum location were approximately $\sqrt{3}$ times the deviations acceptable for new construction. The simple engineering rule of thumb that the need repair limits are just $\sqrt{3}$ times the new construction limits was adopted.

By central and end deviations from a straight edge.—Another derivation of some interest for the straight-edge criterion is afforded by the following consideration. Suppose the central deviation δ between a straight edge and the runway surface were taken according to Fig. 18. In terms of the runway elevations, δ may be written

$$\delta = \frac{y(x+a) + y(x-a)}{2} - y(x) \quad \ldots\ldots\ldots\ldots\ldots \quad (21)$$

The Fourier transform of δ is

$$F_\delta(\Omega) = \frac{1}{2}\left(e^{i\Omega a} + e^{-i\Omega a}\right) F_y - F_y$$

$$= [\cos(\Omega a) - 1]\, F_y(\Omega) \quad \ldots\ldots\ldots\ldots\ldots \quad (22)$$

This, in turn, yields the spectrum

$$\phi_\delta(\Omega) = [\cos(\Omega a) - 1]^2\, \phi_y(\Omega)$$

$$= \left(4 \sin^4 \frac{\Omega a}{2}\right) \phi_y(\Omega) \quad \ldots\ldots\ldots\ldots\ldots \quad (23)$$

The mean-square value of δ is

$$\sigma^2 = \int_0^\infty \phi_\delta(\Omega)\, d\Omega = \int_0^\infty 4\, \phi_y(\Omega) \sin^4\left(\frac{\Omega a}{2}\right) d\Omega \quad \ldots\ldots \quad (24)$$

If the roughness spectrum is assumed to be given by the curve

$$\phi_y(\Omega) = \frac{c}{\Omega^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (25)$$

then Eq. 24 yields the following root-mean-square value of δ

$$\sigma = \sqrt{\frac{\pi\, c\, a}{2}} = \frac{1}{2}\sqrt{\pi\, c\, L} \quad \ldots\ldots\ldots\ldots\ldots \quad (26)$$

in which $L = 2\,a$. With a form factor of $k = \sqrt{2}$, as used previously, the maximum values of δ are found to be in the order of

$$\delta = \sqrt{2}\,\sigma = \sqrt{\frac{\pi\, c\, L}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (27)$$

For values of $c = 0.0000067$ and $c = 0.00002$ as specific choices of new construction and needs repairs spectrum levels, respectively, Eq. 27 gives

$$\delta = 0.00324\sqrt{L}, \qquad \text{new construction}$$

$$\delta = 0.00561\sqrt{L}, \qquad \text{needs repairs}$$

These values are in substantial agreement with the values derived previously (δ herein is similar to $2\sigma'$).

Journal of the

AIR TRANSPORT DIVISION

Proceedings of the American Society of Civil Engineers

DISCUSSION

REINFORCED CONCRETE PAVEMENTS FOR AIRPORTS[a]

Discussion By Gordon K. Ray,[8] F. ASCE, and William G. Westall,[9] M. ASCE

GORDON K. RAY,[8] F. ASCE and WILLIAM G. WESTALL,[9] M. ASCE.—In advocating the use of steel reinforcement in concrete airport pavements, the author draws upon three principal sources for his argument. These are:

1. Highway pavement performance.
2. Corps of Engineers tests on reinforced concrete pavement.
3. Theoretical assumptions.

The purpose of this discussion is to objectively examine each of these.

To keep the subject in proper perspective, it must be recognized that the use of reinforcement in highway pavements is but one of several methods being tried by highway engineers in their continuing search for a design that will provide optimum balance between economy and performance. The principle involved is well stated by an ACI committee in its report on concrete slab dimensions:[10]

> "Determination of the proper length of concrete pavement slabs involves a consideration of several factors, some of which depend upon longitudinal slab stresses, however produced, and others upon the pavement design, construction, maintenance, and past performance under traffic. All of the factors involved must be so balanced against each other that the slab length finally chosen will result in optimum pavement performances. The economic phase of the problem is important and optimum performance must be attained at a cost which, although not necessarily the minimum, does not, however, exceed the benefit produced."

The fact that several state highway departments build reinforced concrete in relatively long panels does not necessarily validate this practice under the criteria quoted previously. Using cement-treated subbases, California and several other states are building concrete pavements with relatively short joint spacing and without dowels for load transfer. The first pavement built on this design in California has shown excellent performance for 14 yr.[11] Nevertheless, the statement used previously also applies here: the successful use of this design does not validate it as the optimum. It must be assumed that each of the many design methods now used by highway construction agencies was

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[a] May, 1960, by August W. Compton.

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[9] Supervising Engr., Airfield Program, Portland Cement Assoc., Chicago, Ill.

[10] "Considerations in the Selection of Slab Dimensions," ACI 53-24, American Concrete Inst.

[11] "Construction Practices on Cement-Treated Subgrades for Concrete Pavements," by F. N. Hveem, presented at 39th Annual Meeting, Highway Research Bd.

adopted in an attempt to obtain a balanced relationship between performance and economy. It appears likely that results from the AASHO Road Test near Ottawa, Ill. will cause revision of some current highway design practices.

Following a comparison of joint spacing in reinforced and non-reinforced pavements, the author states in the last paragraph of his introduction:

> "Both types of design have been used and are now being used for airport pavements. Reasons for using or not using reinforcement are the same as those for highways. Of course, they should be. The volume of traffic on airport pavements is much less than on highways but the wheel loads are many times greater."

The conclusions reached in this quotation are subject to question. Because of a combination of factors, the reasons for using reinforcement in highway pavements cannot be applied without exception to airport pavements. Some of these factors will be discussed because of their special significance.

Compton has pointed out that the traffic volume is much less on airport pavements than on highways. This difference in frequency of loading will bear closer examination.

Airport traffic controllers have estimated that, even under ideal conditions, 1,000 to 1,200 operations per day would equal the maximum rate of utilization of one runway by transport type aircraft. This daily rate is purely theoretical because it is based on the highest hourly rate possible. It does not take into account the reduced rate during weather minimums, nor allow for the slack hours of operation. In actual practice, the number of daily operations will be considerably below the theoretical maximum. Even if it is assumed that an airport pavement might be trafficked 1,000 times daily, this is less than the hourly rate on a busy urban expressway or freeway. Whereas it is true that only a relatively small percentage of the total number of vehicles on the highway will equal or exceed the loading for which the pavement was designed, this is also true of the aircraft that use airport pavements. Considering their much greater traffic volume, highway pavements probably are subjected to the maximum allowable loads with greater frequency than airport pavements are subjected to loads of any kind.

The manner in which loads are applied to pavements is a critical factor in the development of design criteria. Westergaard and others have demonstrated that loading at the free edge of a concrete pavement creates stresses of greater magnitude than interior loading where pavement continuity is provided by load transfer between joints. Airport pavements are seldom, if ever, subjected to loading along a free or unsupported edge. On highways, however, wheels of the heaviest vehicles travel close to the outer edge of the pavement.

Considering their high traffic volume with load channelization at the pavement edge, it must be concluded that highway pavements are subjected to more severe conditions of loading than are airport pavements. The reasons for using reinforcement in highway pavements are not equally applicable to airport pavements.

The author refers frequently (and logically) to Corps of Engineers test data. During the past twenty years the Corps has invested more than $10,000,000 in research and engineering investigations for the development of valid design procedures for airfield pavements. During the same period of time, as the construction agency for the Air Force, they have designed and constructed some $3,000,000,000 worth of military airfield pavements. Probably the Corps of

Engineers has more experience than any other agency in the design, construction, and performance evaluation of pavements built for modern aircraft.

It is interesting, then, to look at their reasons for performing tests on reinforced concrete pavements. In a paper James P. Sale and Ronald L. Hutchinson summed it up as follows:[12]

> "The increased thicknesses (up to 22 inches) required for the 100,000-pound loading at the higher number of coverages being applied, caused increased attention to be focused on methods for reducing these thicknesses through steel reinforcement or prestressing of the pavements. . . . Although it was realized that generally a reinforced rigid pavement would be more costly than an equivalent strength non-reinforced rigid pavement, there was a definite need for such a design criteria to produce some way in which certain pavement thicknesses could be reduced to meet surface grade requirements for different thicknesses in the various traffic areas and, when strengthening an existing pavement, it was impossible to meet surface grade requirements without either removing and replacing large areas of pavements or over-designing certain areas."

Significantly, the reinforced design criteria was developed for the purpose of meeting certain special conditions and no unsatisfactory performance of plain concrete pavement was cited. On the contrary, this statement was included in the same report:

> "The rigid pavement design procedures developed in the investigational program have produced pavements with a proven record of adequacy from the standpoint of construction feasibility, structural capacity, surface smoothness and durability for support of such propeller-driven aircraft as the B-29 and B-36 and more recently for the B-47 and B-52 jet bomber aircraft."

In view of their vast experience in all phases of engineering relating to airfield pavements, it is of further interest to note that the Corps of Engineers design manual[13] (with changes to March 1960) requires reinforced concrete pavement only to meet certain conditions and not as general design criteria.

Much of the author's argument is predicted on assumptions regarding the behavior of concrete pavements built without reinforcement or dowels. It is implied that these pavements can be expected to develop uncontrolled cracking, joint faulting, and general deterioration. This behavior pattern has not been confirmed by engineers who have made performance evaluation surveys of airport pavements that are in service.

Plain concrete pavements that were adequately designed and built under good construction procedures have not developed harmful cracks even under prolonged usage at capacity loading. This is well illustrated in the Corps of Engineers report[14] on the performance of test sections at Sharonville, Ohio.

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12 "Development of Rigid Pavement Design Criteria for Military Airfields," by James P. Sale and Ronald L. Hutchinson, Journal of the Air Transport Div., Proceedings, ASCE, Vol. 85, 1959.

13 "Engineering and Design, Rigid Airfield Pavements," EM 1110-45-303, Corps of Engrs., Dept. of the Army, February, 1958.

14 "Heavy Wheel Load Traffic on Concrete Airfield Pavements," by Frank M. Mellinger, James P. Sale, and Thurman R. Wathan, Proceedings, 36th Annual Meeting of the Highway Research Bd.

These test sections, which included various thicknesses of reinforced and plain concrete pavements, were subjected to 90,000 repetitions of a 100,000-lb twin-wheel loading. The under-designed sections of each type of pavement cracked and broke up under the load repetitions. The fact that the reinforced pavement survived longer after the appearance of a crack seems to have led to conclusions regarding the benefits of reinforcement. However, two of the non-reinforced sections were the only test pavements which did not crack under a number of load repetitions considered the equivalent of 10 yr of traffic.

It has been demonstrated that dowels across contraction joints improve the performance of highway pavements that carry a large volume of heavy truck traffic. As previously discussed, the loading on airport pavements does not approach the highway frequency.

Regarding the assumption that dowels are required to prevent joint faulting in concrete airport pavements, reference is again made to Corps of Engineers design criteria which reflects the information collected in their long-term study of pavement performance. The Corps design manual[13] sets forth these requirements:

> "Dowels will be required across the last three transverse dummy joints back from the ends of all runways, and similar dowel requirements may be included for the ends of other large paved areas where local experience indicates that they are needed."

It is true that the Federal Aviation Agency, requires[15] dowels across contraction joints in aprons, taxiways and the ends of runways "to provide an increased margin of safety with respect to load transfer in these critical areas." This appears to be a carry-over from their 1948 criteria which was published at a time when the effect on pavement of multiple-wheel landing gears was not well understood. The cost of installing dowels, except at free pavement ends, cannot be justified based on airport pavement performance. Within the past several years, the writers have made detailed surveys of millions of square yards of concrete airfield pavements designed and constructed by the Corps of Engineers. These pavements supported all types of military aircraft including the heaviest jet bombers. Even on Air Force training bases, where heavy bomber traffic was at the saturation point, there was no evidence of contraction joint faulting or other pavement defects that could be attributed to the omission of dowels across contraction joints. Built without expansion joints except at abutting structures, airport pavements are restrained from movement to such an extent that aggregate interlock is retained at contraction joints.

Based on his assumption that contraction joints in airport pavements require dowels for proper performance, the author has presented the hypothesis that a reduction of the number of contraction joints will result in financial savings which can be applied to the cost of reinforcement in the longer panels.

This argument loses validity in view of the completely adequate performance of airport pavements built without dowels at the contraction joints. It was stated, also, that a saving in maintenance costs would result from reinforced pavement with fewer joints to maintain. The fallacy of this theory has been conclusively demonstrated by the performance of joints placed between long reinforced panels. Excessive movement, resulting in large joint openings, has made it impossible to keep the joints sealed. The infiltration of noncompressible ma-

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15 "Airport Paving," U. S. Dept. of Commerce, Civ. Aeronautics Administration, October, 1956.

terial into the wide joint openings has caused spalling of concrete along the edges. Attempts to maintain the joints under these conditions have resulted in more maintenance effort than is required for the normal joint spacing in non-reinforced concrete pavement.

The plain concrete pavements built under Corps of Engineers criteria have provided the clean, smooth surfaces required for the operation of modern jet aircraft. Joint openings are minimized by the shorter panels and the infiltration of foreign material is prevented. The possibility of jet engine damage from spalled particles is thus eliminated.

The great weights and peculiar gear configurations of military aircraft have caused the Corps of Engineers to become concerned over the possibility that the pavement thicknesses required may eventually exceed the limits of construction feasibility. This concern need not extend to the pavements required for civil aircraft. The current jet transports, equipped with dual-tandem landing gears, require only about 10 in. to 14 in. of plain concrete pavement even in the critical areas of loading such as taxiways and runway ends. In pavement strength criteria for the various classes of airports, the FAA has seen fit to provide for pavement strength considerably above the current aircraft requirements. This provides a form of insurance against future increases in aircraft weights. For example, at Dulles International Airport, the critical areas of concrete pavement are 15 in. in thickness. This provides sufficient pavement strength to support operations of a 500,000-lb aircraft equipped with the dual-tandem type gear of the 300,000-lb current jet transports. The possibility of these pavements becoming overloaded within the foreseeable future is extremely remote. The pavement thickness is well within the construction capabilities of modern methods and equipment.

This discussion is not intended in any way to disparage the value of steel reinforcement in concrete pavement where conditions justify its use. There is little evidence that the additional cost of reinforcement can be justified for airport pavements. The use of long reinforced panels may be in some ways objectionable from an operational standpoint. Properly designed plain concrete pavement has been proved entirely adequate by many years of performance.

PROCEEDINGS PAPERS

The technical papers published in the past year are identified by number below. Technical-division sponsorship is indicated by an abbreviation at the end of each Paper Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Pipeline (PL), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways and Harbors (WW), divisions. Papers sponsored by the Department of Conditions of Practice are identified by the symbols (PP). For titles and order coupons, refer to the appropriate issue of "Civil Engineering." Beginning with Volume 82 (January 1956) papers were published in Journals of the various Technical Divisions. To locate papers in the Journals, the symbols after the paper number are followed by a numeral designating the issue of a particular Journal in which the paper appeared. For example, Paper 2703 is identified as 2703(ST1) which indicates that the paper is contained in the first issue of the Journal of the Structural Division during 1961.

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MARCH: 2393(IR1), 2394(IR1), 2395(IR1), 2396(IR1), 2397(IR1), 2398(IR1), 2399(IR1), 2400(IR1), 2401(IR1), 2402(IR1), 2403(IR1), 2404(IR1), 2405(IR1), 2406(IR1), 2407(SA2), 2408(SA2), 2409(HY3), 2410(ST3), 2411(SA2), 2412(HW1), 2413(WW1), 2414(WW1), 2415(HY3), 2416(HW1), 2417(HW3), 2418(HW1)[c], 2419(WW1)[c], 2420(WW1), 2421(WW1), 2422(WW1), 2423(WW1), 2424(SA2), 2425(SA2)[c], 2426(HY3)[c], 2427(ST3)[c].

APRIL: 2428(ST4), 2429(HY4), 2430(PO2), 2431(SM2), 2432(PO2), 2433(ST4), 2434(EM2), 2435(PO2), 2436(ST4), 2437(ST4), 2438(HY4), 2439(EM2), 2440(EM2), 2441(ST4), 2442(SM2), 2443(HY4), 2444(ST4), 2445(EM2), 2446(ST4), 2447(EM2), 2448(SM2), 2449(HY4), 2450(ST4), 2451(HY4), 2452(HY4), 2453(EM2), 2454(EM2), 2455(EM2)[c], 2456(HY4)[c], 2457(PO2)[c], 2458(ST4)[c], 2459(SM2)[c].

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FEBRUARY: 2726(WW1), 2727(EM1), 2726(EM1), 2729(WW1), 2730(WW1), 2731(EM1), 2732(SM1), 2733(WW1), 2734(SM1), 2735(EM1), 2736(EM1), 2737(PL1), 2738(PL1), 2739(PL1), 2740(PL1), 2741(EM1), 2742(ST2), 2743(EM1), 2744(WW1), 2745(WW1), 2746(SM1), 2747(WW1), 2748(EM1), 2749(WW1), 2750(WW1)[c], 2751(EM1)[c], 2752(SM1)[c], 2753(PL1)[c], 2754(ST2)[c], 2755(PL1).

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c. Discussion of several papers, grouped by divisions.

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